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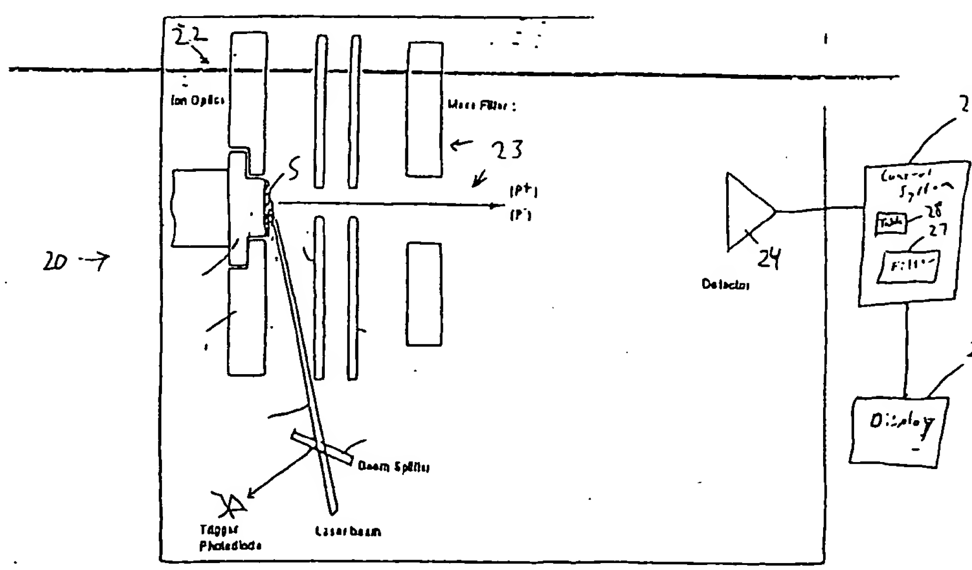

(57) Abstract

A method and system of detecting mass to charge ratio of ions. The method includes producing charged ions in a vacuum, accelerating the charged ions in an electric field into a free flight tube and detecting the charged ions at a detector associated with the free flight tube. A control system selects a bandwidth for filtering a signal produced by the detector and the signal produced by the detector is then filtered with a variable width digital filter based upon the selected bandwidth. The bandwidth for filtering the signal may be selected from a look–up table within the control system based upon the mass to charge ratio of an ion of interest. Alternatively, a peak bandwidth within the signal produced by the detector may be determined and the signal produced by the detector may then be filtered with the variable width digital filter based upon the determined peak bandwidth.

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VARIABLE WIDTH DIGITAL FILTER FOR TIME-OF-FLIGHT MASS SPECTROMETRY

This application claims priority from U.S. Provisional Patent Application Serial No. 60/134,072 (Atty. Docket No. 016866-003400), filed May 13, 1999, the disclosure of which is incorporated herein by reference in its entirety.

BACKGROUND OF THE INVENTION

1. Field Of The Invention

The present invention relates to a software filter for use with time-of-flight mass spectrometry, and more particularly, to a variable width digital filter for use with time-of-flight mass spectrometry.

2. Description Of The Prior Art

With reference to Figure 1, time-of-flight mass analyzers or spectrometers consist of a source/extraction region 10, a drift region 11 and a detector 12. In the source region, an electrical field (E=V/s) accelerates the ions to a constant energy. The drift region is field free and ions cross the drift region with velocities that are inversely proportional to the square root of their respective masses. Thus, lighter ions have higher velocities and arrive at the detector sooner than heavier ions.

In the ideal situation where ions are formed at a single point in the source region, ions are accelerated to the same final kinetic energy:

$$\frac{1}{2}mv^2 = eV$$

and cross the drift regions with velocities:

$$v = \left[\frac{2eV}{m}\right]^{1/2}$$

and flight times:

$$t = \left[\frac{m}{2eV}\right]^{1/2}$$

These relationships depend upon the square root of the ions' masses.

In a mass spectrometer, the mass resolution is defined as m/Δm. In a time-of-flight mass spectrometer in which ions are accelerated to constant energy:

$$\frac{m}{\Delta m} = \frac{t}{2\Delta t}$$

In time-of-flight mass spectrometers, it is not unusual to see a wide mass range being scanned at any given time. Ions with molecular weights between 100 and several thousand Da, ions ranging from 3,000 to about 20,000 Da, as well as all ions greater than 20,000 Da, are typically simultaneously studied in such techniques as Surface Enhanced Laser Desorption Ionization SELDI and Matrix Assisted Laser Desorption Ionization (MALDI).

The fundamental physical processes involved in the previously mentioned processes are such that signals created by heavy ion populations are generally composed of lower frequency components than their light ion counter parts. For signals created by light ion populations, broad detection bandwidths are required to accurately sample these fast transients allowing for enhanced resolution mass measurement. Signals from heavier ion populations typically do not possess significant high frequency components and thus may be sampled at significantly lower bandwidth frequencies. Table 1 lists theoretical major frequency components and estimates peak widths and mass resolutions of various ion signal populations along with their estimated times of flight and molecular weights as generated by a SELDI or MALDI time-of-flight mass spectrometer with one-meter drift region and 25 keV total energy.

TABLE 1

Ion Molecular Weight (m/z)	Ion Flight Time (uSec)	Major Component Frequency (MHz)	Peak Width At Half Height (uSec)	Mass Resolution
500	10.2	740	0.0010	5000
1,000	14.4	500	0.0016	4500
2,000	20.4	250	0.0034	3000
5,000	32.2	70	0.0134	1200
15,000	55.8	19	0.0254	1100
40,000	91.1	2	0.3037	150
150,000	176.3	.290	1.7600	50
250,000	227.6	.130	3.8000	30
500,000	321.9	.063	8.0500	20

Thus, by reviewing Table 1, it can be seen that the peak width at half height and mass resolution of a given ion population can be correlated to ion flight time for a given ion total kinetic energy and a given free flight distance. Most time-of-flight mass spectrometers incorporate a fixed drift region distance. Furthermore, these devices also operate using either a fixed level or precisely selectable levels of ion acceleration, thus allowing qualified approximations of ion total kinetic energy. Under such conditions, it would be possible to predict the signal frequency requirements for a variety of ion populations based upon their time of detection.

The wider a peak width is, the more ions of different "sizes" may be contained within the particular ion population that is being detected. Hence, it is desirable to accurately display peak widths.

Just as in other forms of spectroscopy, time-of-flight mass spectrometry has several sources of signal noise. Such signal noise may increase peak widths. Typical noise sources such as sampling noise (alaising), Johnson noise, and flicker noise contribute to the total system noise. However, sensible engineering approaches will often reduce these noise sources to insignificant levels. Often, the most frequently encountered noise in time-of-flight mass spectrometry measurements is high frequency noise created by the detection apparatus. The combined use of secondary ions/electron generation schemes with high gain electroemissive detection surfaces frequently introduce high frequency noise that is the direct result of spurious background gas ionization, thermal or low energy photon noise (dark current noise), as well as higher energy photon or other particle-induced noise. Thus, when considering the above factors regarding ion signal component frequencies and time-of-flight mass spectrometry noise characteristics, it is evident that a fixed width filter is not a desirable solution for addressing noise problems. A filter in which the bandwidth may be varied over time range of the time-of-flight spectrum may better optimize the tradeoffs between increasing the signal to noise ratio while having the least negative effect on the mass resolution.

SUMMARY OF THE INVENTION

A method of detecting mass to charge ratio of ions in accordance with the present invention includes producing charged ions in a vacuum, accelerating the charged ions with an electric field into a free flight tube, and detecting the charged ions at a detector associated with the free flight tube. With a control system, a bandwidth for

filtering a signal produced by the detector is selected. The signal produced by the detector is then filtered with a variable width digital filter based upon the selected bandwidth.

In accordance with one aspect of the present invention, the bandwidth for filtering the signal is selected from a look-up table within the control system based upon the mass to charge ratio of an ion of interest.

In accordance with a further aspect of the present invention, the method of detecting mass to charge ratio of ions further includes determining a peak bandwidth within the signal and filtering the signal produced by the detector with the variable width digital filter based upon the determined peak bandwidth.

Accordingly, the present invention provides a system and method, especially well suited for time-of-flight mass spectrometry wherein the width of a digital filter of varied over the mass spectrum to optimize the signal to noise improvement throughout the mass range. This is done without significantly compromising the mass resolution.

Other features and advantages of the present invention will be understood upon reading and understanding the detailed description of the preferred exemplary embodiments found hereinbelow, in conjunction with reference to the drawings, in which like numerals represent like elements.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a schematic illustration of a time-of-flight mass spectrometer;

Figure 2 is a schematic diagram of one possible embodiment of a mass spectrometer system in accordance with the present invention; and

Figures 3-6 are graphs illustrating the effect of a variable width digital filter in accordance with the present invention on signals from a mass spectrometer.

DETAILED DESCRIPTION OF THE PREFERRED EXEMPLARY EMBODIMENTS

Generally, a mass spectrometer 20 charges or ionizes molecules of a sample S into ions P in a vacuum 21. These ions are accelerated by an electric field produced by an ion-optic assembly 22 into a free flight tube 23. The velocity at which the ions may be accelerated is proportional to the square root of the accelerating potential, the square root of the charge of the molecule and inversely proportional to the square root of

the mass of the molecule. The charged ions travel, i.e., "drift" down the time-of-flight tube to a detector 24.

Detector 24 generates a signal, generally an electronic signal, that is generally received, and preferably stored, in a control system 25, such as for example, a computer or the like. The signal is then displayed on some type of a display screen 26, such as a computer monitor, an oscilloscope, etc. Such viewing may be done either in real time, i.e., as the signal is received from the detector, or from the stored signal.

As previously discussed, time-of-flight mass spectrometry has several sources of signal noise that include, for example, sampling noise (alaising), Johnson noise, and flicker noise. Some of the most frequently encountered noise in time-of-flight spectrometry measurements is high frequency noise created by the detector. Often the detector includes secondary ion/electron generation schemes with high gain electroemissive detection surfaces that frequently introduce high frequency noise that is the direct result of spurious background gas ionization, thermal or low energy photon noise (dark current noise), as well as higher energy photon or other particle-induced noise.

A digital filter is a linear/shift-variance system for computing a discreet output sequence form a discreet input sequence. The digital filter is applied to a series of equally spaced data values $f_i \equiv f(t_i)$, where $t_i \equiv t_0 + \Delta$ for some constant sample spacing Δ and $i = \ldots -2,-1,0,1,2\ldots$ The simplest type of digital filter, commonly referred to as a fixed width moving average filter, replaces each value f_i by a linear combination g_i of itself and some number of nearby neighbors,

$$g_i = \sum_{n=n_L}^{n_R} c_n f_{i+n}$$

Here n_L and n_R are the numbers of data points used.to the left and to the right of data point i respectively. n_L and n_R are both constants, thus, the filter has a constant width of $n_L + n_R + 1$.

Replacing constants n_L and n_R $with$ $n_{Li} = n_L(t_i)$ and $n_{Ri} = n_R(t_i)$ creates a variable width digital filter.

$$g_i = \sum_{n=-n_{L_i}}^{n_{R_i}} c_n f_{i+n}$$

Such a variable width digital filter 27 is included with control system 25 and is applied to signal data received from the detector to increase the signal to noise ratio of the spectrum. The variable width digital filter utilizes the fact that data is over-sampled in the time domain. Increasing the filter width decreases the signal bandwidth, and can improve the signal to noise ratio if the signal of interest is a far lower frequency than the noise. Thus, the variable width digital filter offers the ability to filter the data after the data has been recorded without permanently changing the raw spectrum data. Therefore, the data may be examined and the filter adjusted to optimize the trade-offs between signal to noise enhancement and resolution that filtering the data imposes.

In a preferred embodiment, a look-up table 28 is provided within the control system for selecting the bandwidth of the variable width digital filter. The bandwidth is selected based upon observed or theoretical data related to varying mass to charge ratios of ions. Alternatively, the control system may be programmed such that upon receiving signals from detector 24 or upon analyzing saved or recorded signals already received from the detector, the widths of the various peaks within the signal are determined in the bandwidth for the variable width digital filter as used therein.

Figures 3-6 illustrate the improvement in signal to noise and resolution that a variable width filter in accordance with the present invention provides. The same spectrum is compared unfiltered, with a 51 point fixed moving average filter, and with a variable width moving average filter. The data was acquired at 250 MHz, making the 51 point moving average filter .024 microseconds wide. The variable width filter varies its width in points by interpellating a table of Mz to expected peak widths. Table 2 illustrates an example of width values that were used to calculate the variable filter widths for the figures. In the figures, the X-axis represents the mass/charge ratio (M/Z) while the Y-axis represents arbitrary ion intensity units.

TABLE 2

Variable Width Filter Table

Position (Daltons)	Width (Daltons)
0	10
33000	650
147000	5500

Figure 3 illustrates the entire spectra of example data. Figures 4-6 illustrate the detailed view of peak 1, which occurred at 6,634 daltons, a detailed view of peak 2, which occurred at 18,123 daltons, and a detailed view of the third peak, which occurred at 70,567 daltons, respectively. Tables 3 and 4 illustrate the effect of filtering on M/Z resolution and the effect of filtering on the signal to noise ratio.

TABLE 3

Effect Of Filtering On M/Z Resolution

		M/Z Resolution		
Peak #	M/Z	No Filter	51 Point Fixed	Variable Width
1	6634	147	71	135
2	18123	82	42	63
3	70578	40	33	42

TABLE 4

Effect Of Filtering On Signal To Noise Ratio

		Signal To Noise		
Peak #	M/Z	No Filter	51 Point Fixed	Variable Width
1	6634	10	157	38
2	18123	21	616	424
3	70578	.79	24	106

Thus, it can be seen that with a fixed width filter, the optimized filter value for mass resolution and signal to noise enhancement can only occur at a relatively small portion of the spectrum. With a variable width filter in accordance with the present invention, the entire spectrum may be optimized. Accordingly, it is easier to isolate peaks and therefore isolate ions as opposed to groups of ions.

Appendix A contains source code that provides an example of a variable width digital filter for time-of-flight mass spectrometry in accordance with the present invention written in C++.

Thus, the present invention provides a digital filter for time-of-flight mass spectrometry that varies the width of the filter over the mass spectrum to optimize the signal to noise improvement throughout the mass range without significantly

compromising the mass resolution. This is accomplished by predicting the required filter width at a given time in the spectrum The predicted widths may be generated from theoretical or observed spectra.

Although the invention has been described with reference to specific exemplary embodiments, it will be appreciated that it is intended to cover all modifications and equivalents within the scope of the appended claims.

APPENDIX A

Example Source Code for a Variable Width Filter in C++:

```
void CGFilterVarWidth::FilterData(const CArray<double,double> &rawData,
                                  CArray<double,double> &filteredData,
                                  CRange<long> &usableRange) const
{
        long n = rawData.GetSize();
        filteredData.SetSize(n);

        if (n == 0)
        {
                usableRange.Setup(0, 0);
                return;
        }

        ASSERT(m_spectrum != NULL);

        // Prepare an array of filter widths.
        CArray<double,double> ident;
        CArray<double,double> width;
        CArray<long,long> halfWidth;
        ident.SetSize(n);
        for (long i = 0; i < n; ++i)
                ident[i] = i;

        m_varWidth->EvaluateOnGrid(m_spectrum, CGSpecFun::IUDP, CGSpecFun::DUNPWid, ident, width);

        halfWidth.SetSize(n);
        for (i = 0; i < n; ++i)
                halfWidth[i] = (long)(width[i]) / 2;

        // Do the filtering.
        long haveFrom = 0, haveTo = -1;
        double sum = 0;
        long usableFrom = 0, usableTo = n - 1;

        for (i = 0; i < n; ++i)
        {
                long hw = halfWidth[i];
                if (hw < 0)
                        hw = 0;
                long from = i - hw;
                long to = i + hw;

                if (from < 0)
                {
                        from = 0;
                        if (usableFrom < i + 1)
                                usableFrom = i + 1;
                }

                if (to >= n)
                {
                        to = n - 1;
                        if (usableTo > i - 1)
                                usableTo = i - 1;
                }


                if (from < haveFrom)
                {
                        for (long k = from; k < haveFrom; ++k)
                                sum += rawData[k];
                        haveFrom = from;
                }
                else if (from > haveFrom)
                {
                        for (long k = haveFrom; k < from; ++k)
                                sum -= rawData[k];
                        haveFrom = from;
                }

                if (to > haveTo)
                {
                        for (long k = to; k > haveTo; --k)
```

```
                        sum += rawData[k];
                haveTo = to;
            }
            else if (to < haveTo)
            {
                for (long k = haveTo; k > to; --k)
                        sum -= rawData[k];
                haveTo = to;
            }

            filteredData[i] = sum / (to - from + 1);

    }

    // Check for the 'nothing usable' case.
    if (usableFrom >= usableTo)
    {
            int k = n/2;
            usableRange.low = usableRange.high = k;
            double v = filteredData[k];
            for (i = 0; i < usableFrom; ++i)
                    filteredData[i] = v;
    }
    else
    {
            usableRange.low = usableFrom;
            usableRange.high = usableTo + 1;

            // Fill the tails with constant. filteredData[0...usableRange.low-1] =
filteredData[usableRange.low] and
            // filteredData[usableRange.high...N-1] = filteredData[usableRange.high-1]
            for (i = 0; i < usableFrom; ++i)
                    filteredData[i] = filteredData[usableFrom];
            for (i = usableTo + 1; i < n; ++i)
                    filteredData[i] = filteredData[usableTo];
```

WHAT IS CLAIMED IS:

1. A method of detecting mass to charge ratio of ions, the method comprising:

producing charged ions in a vacuum;

accelerating the charged ions with an electric field into a free-flight tube;

detecting the charged ions at a detector associated with the free-flight tube;

selecting, with a control system, a bandwidth for filtering a signal produced by the detector; and

filtering the signal produced by the detector with a variable width digital filter based upon the selected bandwidth.

2. The method of claim 1 wherein the bandwidth for filtering the signal is selected from a look-up table within the control system based upon the mass to charge ratio of an ion of interest.

3. The method of claim 1 further comprising:

determining a peak bandwidth within the signal produced by the detector; and

filtering the signal produced by the detector with the variable width digital filter based upon the determined peak bandwidth.

4. A system for detecting mass to charge ratio of ions, the system comprising:

a. a mass spectrometer comprising:

i. a vacuum;

ii. an ion-optic assembly adjacent the vacuum;

iii. a free-flight tube adjacent the ion-optic assembly; and

iv. a detector adjacent the free-flight tube;

b. a control system for receiving a signal from the detector; and

c. means for displaying the signal from the detector;

wherein the control system includes a variable width digital filter for filtering the signal produced by the detector based upon a desired bandwidth corresponding to a peak width of the signal corresponding to an ion of interest.

5. The system of claim 4 wherein the control system includes a look-up table for selecting the desired bandwidth based upon a mass to charge ratio of an ion of interest.

6. The system of claim 4 wherein the means for displaying comprises an oscilloscope.

Time-of-Flight Mass Spectrometer

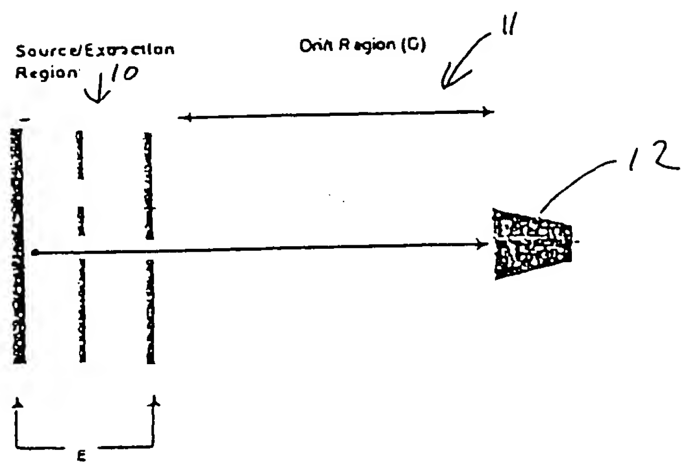
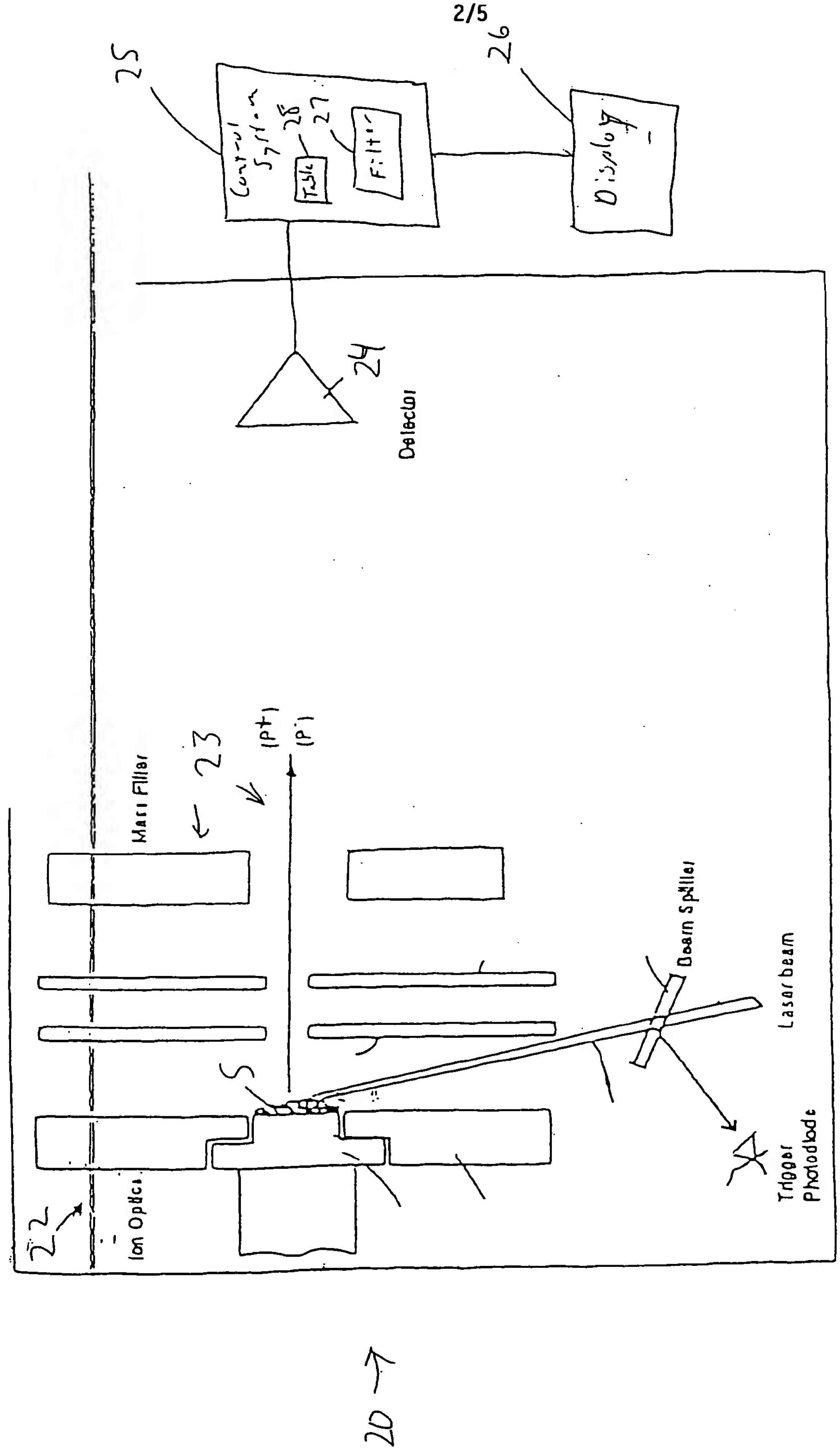


Figure 1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Control System
28
27
Table
Filter
26
Display
24
Detector
Mass Filter
23
(P+)
(P-)
Beam Splitter
Laser beam
5
22
Ion Optics
Trigger Photodiode
20

Figure 2

Figure 3 Example spectra data with different digital filters

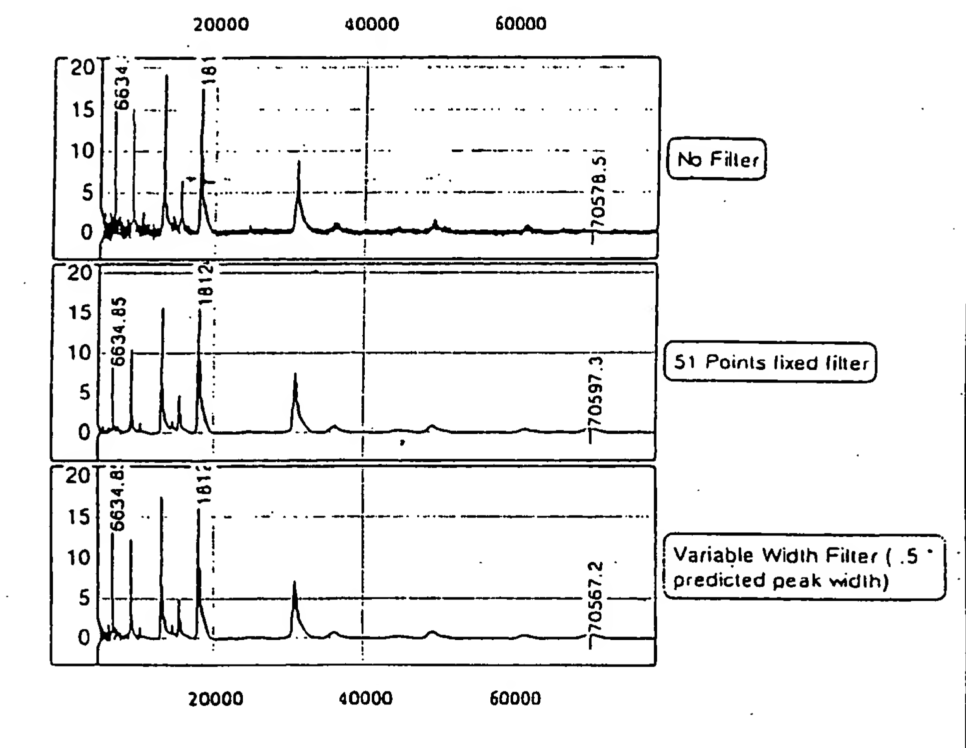


Figure 4 Detailed view of Peak 1

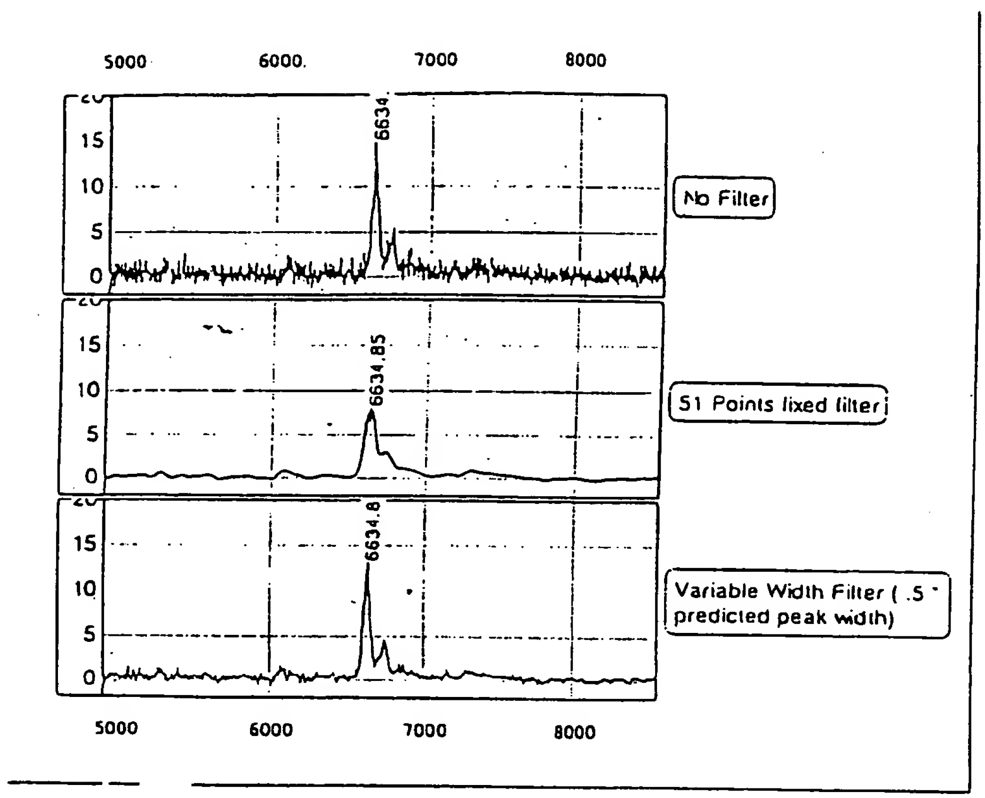


Figure 5 Detailed view of Peak 2

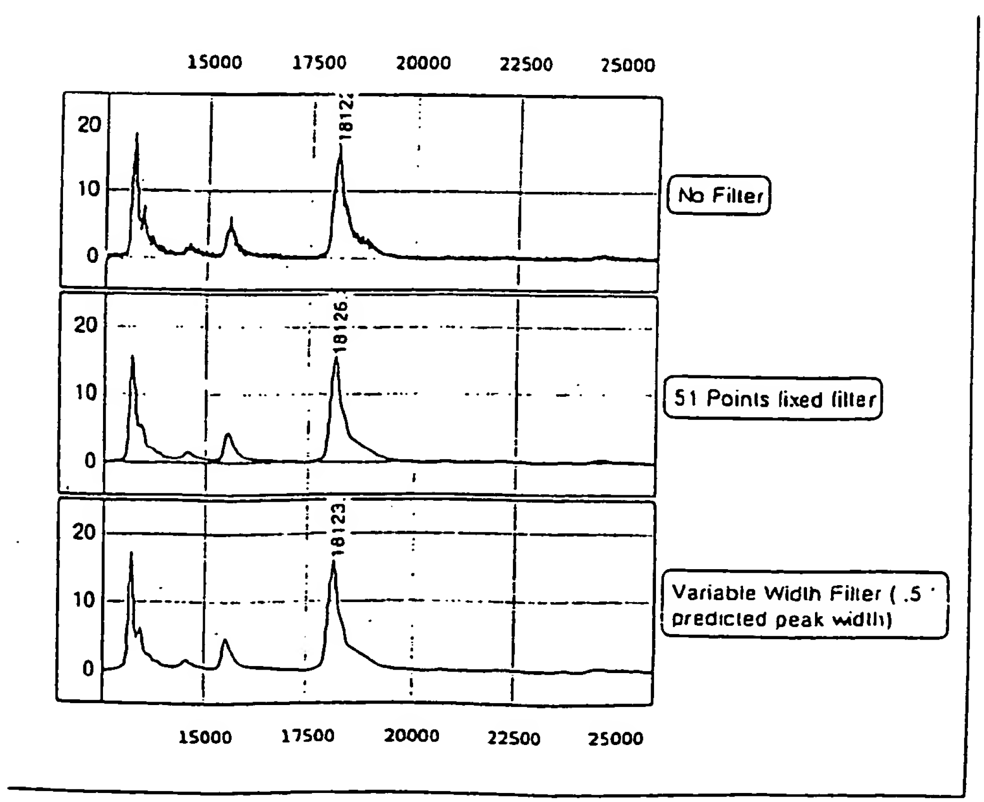
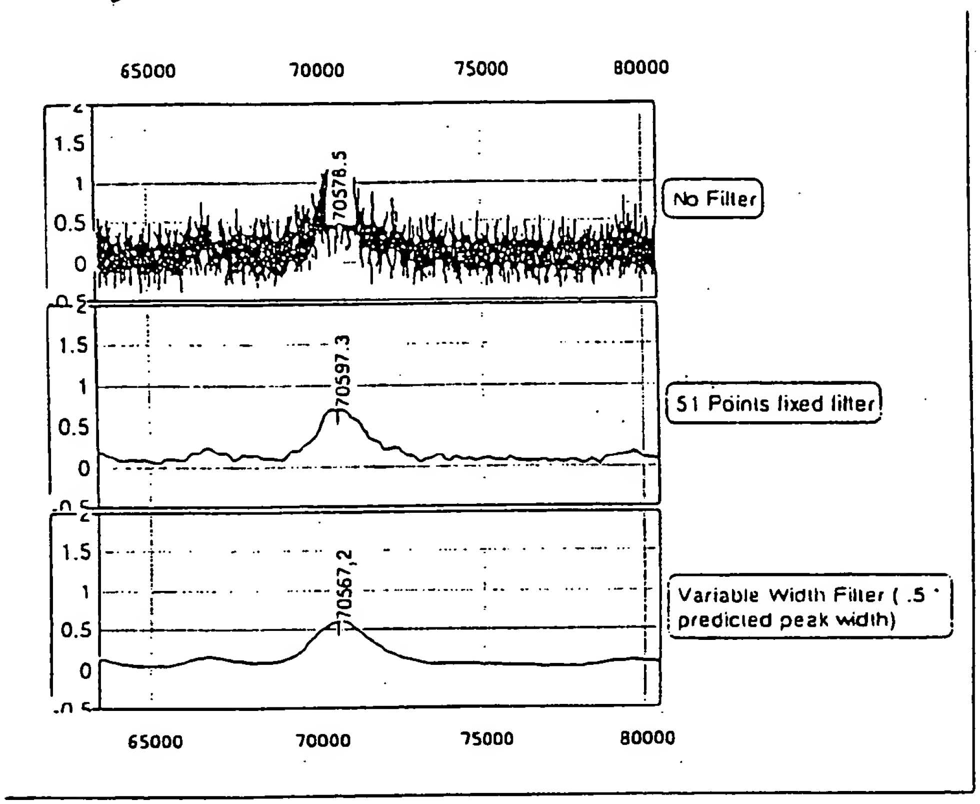


Figure 6 Detailed view of peak 3



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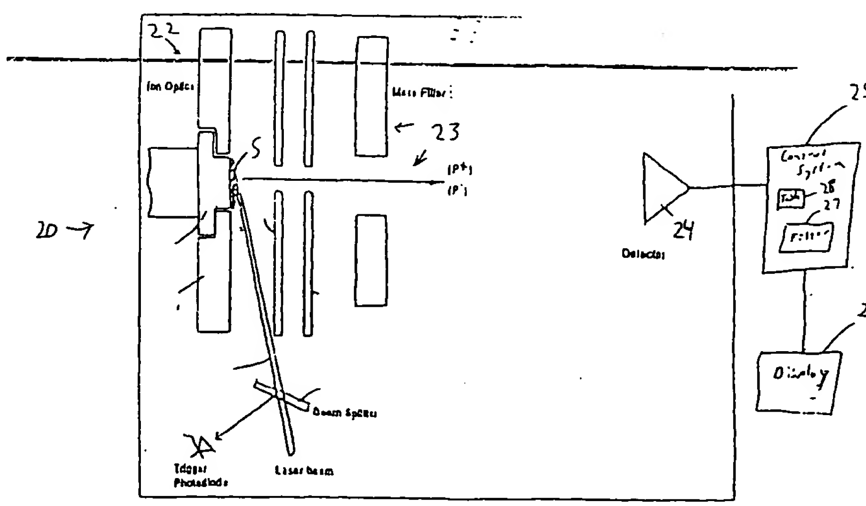

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INTERNATIONAL SEARCH REPORT

Internal Application No
PCT/US 00/13153

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 H01J49/40

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 H01J

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, PAJ, WPI Data, INSPEC, COMPENDEX

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	RAZNIKOV V. V. ET AL.: "New Approaches to Transformation and Analysis of Mass-Spectrometric and Chromatographic/Mass-Spectrometric Information" APPL. ENERGY: RUSSIAN JOURNAL OF FUEL, POWER AND HEAT SYSTEMS, vol. 35, no. 1, 1997, pages 71-86, XP000941024 pages 77, 2nd and 3rd complete paragraphs paragraph bridging pages 81 and 82 page 82, 4th complete paragraph ---	1,2,4,5

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[X] Further documents are listed in the continuation of box C.

[ ] Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
2 November 2000	15/11/2000

Name and mailing address of the ISA	Authorized officer
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C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	BROMBA M U A ET AL: "APPLICATION HINTS FOR SAVITZKY-GOLAY DIGITAL SMOOTHING FILTERS" ANALYTICAL CHEMISTRY,US,AMERICAN CHEMICAL SOCIETY. COLUMBUS, vol. 53, no. 11, 1 September 1981 (1981-09-01), pages 1583-1586, XP000716115 ISSN: 0003-2700 the whole document ---	1-6
A	BIERMANN G. AND ZIEGLER H.: "Properties of a Variable Digital Filter for Smoothing and Resolution Enhancement" ANAL. CHEM. , vol. 58, 1986, pages 536-539, XP000942988 the whole document ---	1-6
A	BROMBA M. AND ZIEGLER H.: "Variable Filter for Digital Smoothing and Resolution Enhancement of Noisy Spectra" ANAL. CHEM., vol. 56, 1984, pages 2052-2058, XP000942983 the whole document ---	1-6
A	HEDFJAELL B ET AL: "COMPUTERIZED FAST-SCANNING GAS CHROMATOGRAPH-MASS SPECTROMETER" ANALYTICAL CHEMISTRY,AMERICAN CHEMICAL SOCIETY. COLUMBUS,US, vol. 47, no. 4, February 1975 (1975-02), pages 666-670, XP000940954 ISSN: 0003-2700 page 667, right-hand column, line 7,8 page 669, left-hand column, paragraph 2 -----	1-6

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